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Control of maximal and submaximal vertical jumps

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ABSTRACT

VAN ZANDWIJK, J. P., M. F. BOBBERT, M. MUNNEKE, and P. PAS. Control of maximal and submaximal vertical jumps. *Med. Sci. Sports Exerc.*, Vol. 32, No. 2, pp. 477–485, 2000. **Purpose:** It was investigated to what extent control signals used by human subjects to perform submaximal vertical jumps are related to control signals used to perform maximal vertical jumps. **Methods:** Eight subjects performed both maximal and submaximal height jumps from a static squatting position. Kinematic and kinetic data were recorded as well as electromyographic (EMG) signals from eight leg muscles. Principal component analysis was used analyze the shape of smoothed rectified EMG (SREMG) histories. Jumps were also simulated with a forward dynamic model of the musculoskeletal system, comprising four segments and six muscles. First, a maximal height jump was simulated by finding the optimal stimulation pattern, i.e., the pattern resulting in a maximum height of the mass center of the body. Subsequently, submaximal jumps were simulated by adapting the optimal stimulation pattern using strategies derived from the experimental SREMG histories. **Results:** SREMG histories of maximal and submaximal jumps revealed only minor differences in relative timing of the muscles between maximal and submaximal jumps, but SREMG amplitude was reduced in the biarticular muscles. The shape of the SREMG recordings was not much different between the two conditions, even for the biarticular muscles. The simulated submaximal jump resembled to some extent the submaximal jumps found in the experiment, suggesting that differences in control signals as inferred from the experimental data could indeed be sufficient to get the observed behavior. **Conclusions:** The results fit in with theories on the existence of generalized motor programs within the central nervous system, the output of which is determined by the setting of parameters such as amplitude and relative timing of control signals. **Key Words:** HUMAN JUMPING, ELECTROMYOGRAPHIC ANALYSIS, MATHEMATICAL MODELING, OPTIMIZATION

Human subjects are able to execute most motor tasks at different levels of performance. When a given task is executed maximally, the subject attempts to achieve the highest performance possible. On the other hand, when submaximal performance is asked for, the subject attempts to attain a certain level of performance, which may be prescribed by the experimenter. It is the task of the central nervous system (CNS) to generate in each case an appropriate set of control signals to all muscles involved in execution of the task. In case of performing a task maximally, this might be relatively easy from a control point of view, because there exists a unique set of control signals yielding maximal performance. These optimal control signals can be the result of some learning process in which controls are adapted over time to yield finally those giving maximal performance. Providing control signals for submaximal performance of a task is, however, more difficult for a number of reasons. In the first place, there exist, in principle, different sets of control signals which all yield the same submaximal performance. Besides this, there are many levels of submaximal performance possible, each of which requires an appropriate set of control signals.

On the basis of these considerations, it remains an intriguing puzzle how the CNS generates control signals for different levels of performance of a motor task. It seems unlikely that the CNS explicitly calculates suitable control signals for each level of performance using some internal representation, because most motor tasks can be initiated almost instantaneously. Also, it does not appear to be a feasible option that control signals for each level of submaximal achievement of a motor task are stored somewhere in the CNS in the form of a motor program. In that case, retrieval of the appropriate motor program for each level of performance would be a problem. Besides this, it would be difficult to explain successful performance at new levels of performance. An elegant alternative which circumvents the storage and novelty problem is based on the concept of generalized motor programs (9). A generalized motor program is a template motor program for a particular class of movements, the output of which is determined by the setting of certain parameters. Once a certain rule is provided to adjust parameters within the generalized motor program, this program can be used to provide control signals for both maximal performance of a task and all levels of submaximal performance.

This paper addresses the issue how the CNS generates control signals in case of multi-joint vertical squat jumping

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to different heights. Vertical jumping belongs to the class of explosive movements. These movements are characterized by a short execution time and are aimed at giving a high velocity to a part of the body. Because of the short execution time, afferent feedback can only play a limited role in the control of such movements. This means that control signals must to a large extent be preprogrammed and that therefore controlling such movements relies heavily on storage capacity of the CNS. Furthermore, vertical squat jumping is attractive for studying movement control because performance can be unambiguously defined in terms of jump height. Since the focus will be on general organizing principles in the control of explosive movements, it will first be investigated whether different subjects consistently perform submaximal vertical squat jumps in a similar way. Secondly, differences in control signals between maximal and submaximal squat jumping will be analyzed to see whether control signals for these two levels of performance are related. For this purpose, one requires a measure for control signals to each muscle involved in the execution of the movement.

Although measures for neural control signals cannot be obtained directly, one can record electromyographical signals (EMG signals) from active muscles in human subjects. Despite the fact that these EMG signals are electrical outputs of muscle, they are closely related to neural control signals to the muscles (e.g., 6,8,15). Therefore, in order to investigate the control strategy employed during the execution of maximal and submaximal squat jumping, EMG signals recorded during maximal and submaximal squat jumping are compared. Differences observed in EMG signals between the two conditions could be the result of parameter adjustment in the generalized motor program used in the execution of squat jumping. In an simulation study, van Soest and Bobbert (10) proposed a control strategy for generating control signals in case of submaximal squat jumping, which results in scaling of net joint moments and hence identical kinematics at different speeds of movement. Such a control strategy would provide the advantage that performance remains predictable.

Finally, it will be examined whether the differences in EMG signals found between maximal and submaximal jumping are sufficient for obtaining submaximal performance by means of numerical simulation of the push-off phase in vertical squat jumping. To this end, control signals pertaining to a maximal height squat jump in a model of the human musculo-skeletal system are adapted according to the differences in EMG signals found between maximal and submaximal jumping, and it will be examined to what extent the resulting jumps in the model resemble submaximal squat jumps found in human subjects.

METHODS

Subjects

Eight male volunteers (age 26 ± 3 yr, height 1.91 ± 0.05 m, body mass 83 ± 7 kg) participated in this study. Informed consent was obtained from each subject according to the policy statement of the American College of Sports Medicine.

Protocol

Each subject performed maximal and submaximal jumps from the same static squatting position. To help the subject reproduce the same initial position each time a device was used which consists of two boards fixed to a pole in a hinge. The angle of the boards with the pole as well as the height of hinge can be varied independently. First, the subject assumed a freely chosen initial position. In this position, the angles of both boards and the height of the hinge were set to match hip and knee segment angles and height of the hip joint as closely as possible. It is easily shown that once these three parameters are fixed the initial position is determined unambiguously.

Before all subsequent jumps, subjects adjusted their initial position to the device to match the initial position of the first jump as accurately as possible. After this adjustment, the device was pulled back by the experimenter and the subject performed the jump. The subject was instructed keep his arms crossed behind his back during execution of the jumps, to jump without making preparatory countermovement and to initiate the jump as soon as possible after a beep signal. All subjects performed both maximal height and submaximal height jumps. In the case of maximal height jumping, the subjects were instructed to jump as high as possible. In the case of submaximal jumping, a target height was indicated by means of a small light source that was placed at some distance behind a narrow slit. The light source could only be seen when looked at horizontally through the slit. Subjects were instructed to jump to such a height, that they could just see the lightsource. This procedure ensured that the subjects attained about the same jump height each time they performed a submaximal jump. Jump height is defined as the height reached by the centre of mass (CM) of the body at the apex of the jump relative to the height of the CM of the body in upright standing. Figure 1 schematically shows the setup used.

After some practice jumps, each subject performed three maximal height jumps from which averaged maximal jump height was calculated. Subsequently, the light source was placed at a height corresponding to approximately 75% of maximal jump height. By choosing such a high percentage, it was hoped that control of the movement remained open loop in case of submaximal jumping, which might not be the case if a smaller percentage of maximal jump height was selected. Next, each subject performed six maximal and eight submaximal jumps in random order.

Kinematics and Kinetics

In this study reflecting markers were placed on fifth metatarsophalangeal joint, calcaneus, lateral malleolus, knee joint (on the lateral collateral ligament at the height of the joint cleft), greater trochanter, and neck (at the height of the fifth cervical vertebra). These markers defined the

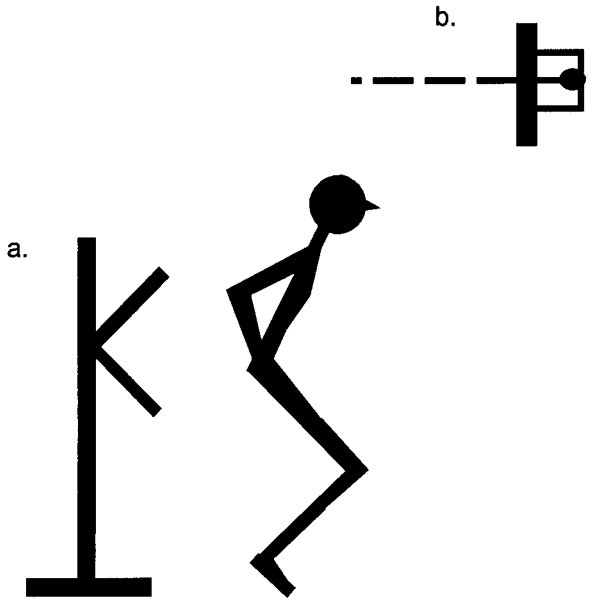

Figure 1—Schematic view of the setup used in the experimental study. *a,* Device used to help subject reproduce the same starting position each time they produced a vertical squat jump. *b,* Apparatus containing a light source to indicate target height in case of submaximal jumping.

position of the four body segments: feet, lower legs, upper legs, and head-arms-trunk (HAT). During jumping kinematic data were obtained using high speed video (VICON, Oxford Metrics Ltd.) at a sample rate of 100 Hz. Simultaneously, vertical and fore-aft components of the ground reaction force and its point of application were measured using a force platform (Kistler 9281B, Kistler Instruments Corp., Amherst, NY) and sampled at 200 Hz.

Electromyography

Electromyographic signals (EMG signals) of eight muscles of one leg were recorded during the execution of the jumps using pairs of surface electrodes (Meditrace ECE 1801) after standard skin preparation techniques (2). The muscles selected were lateral and medial head of m. gastrocnemius, m. soleus, m. semitendinosus, long head of m. biceps femoris, m. vastus lateralis, m. rectus femoris, and m. gluteus maximus. The electrical signals of the muscles were amplified (Disa 15 C01, Disa Electronics, Skovlunde Denmark) and 7-Hz high-pass filtered to eliminate movement artifacts. Subsequently the electrical signals were rectified, 22-Hz low-pass filtered and sampled at 200 Hz, yielding smoothed rectified EMG signals (SREMG signals).

Treatment of Data

For each subject, the three highest maximal jumps and the three lowest submaximal jumps were selected for further analysis. Kinematic and kinetic variables of different jumps were synchronized at the instant the subject left the ground (subsequently referred to as toe-off) and truncated to contain only the last 750 ms of the push-off phase before averaging. The SREMG recordings were synchronized the same way and additionally for each trial baseline activity (i.e., activity of the muscles before the jump was executed) was subtracted before averaging.

Electromyographic Data Analysis

Differences in control signals to the muscles between maximal and submaximal jumps may consist of a combination of (i) a change in amplitude of control signals to the muscles, (ii) a change in shape of control signals to the muscles, and (iii) a change in relative timing of control signals to the muscles. So the SREMG recordings of the averaged maximal and submaximal jumps were searched for all of these possibilities, using the following methods:

Amplitude of the control signals. Differences in amplitude of the control signals to the muscles were quantified by computing the ratio of the time integrals of the SREMG histories of the averaged submaximal jump to those of the averaged maximal jump. So if a muscle is less active in case of submaximal jumping, this will lead to a ratio which is smaller than one. Subsequently, for each muscle these ratios were averaged across subjects and it was tested whether the averaged ratio differed significantly from 1.0 using a Student *t*-test for paired comparisons at a level of significance of 5%.

Shape of the control signals. To quantify the difference in shape of the control signals to the muscles in maximal and submaximal jumping principal component analysis (PCA) was performed on averaged maximal and submaximal SREMG histories for each muscle (see also: 3,4). This statistical technique computes from a set of data waveforms $\{s_i\}$ a set of orthonormal principal component waveforms $\{pc_j\}$ and a set of weighting coefficients $\{c_{ij}\}$, such that

$$s_i = \sum_j c_{ij} pc_j \forall i \quad (1)$$

By definition, the first principal component is the best mean square representation of all data waveforms in the set $\{s_i\}$, the second principal component is the best mean square representation to the data waveforms $\{s_i\}$ after the first component has been subtracted, and so on. The fraction f_1 of the variance of the set $\{s_i\}$ explained by the first principal component equals

$$f_1 = \frac{\sum_i c_{i1}^2}{\sum_{ij} c_{ij}^2} \quad (1)$$

If there is a large difference in shape of control signals between maximal and submaximal jumping, this is reflected in a small fraction of variance explained by the first principal component. Before PCA, mean values were subtracted from the SREMG histories, and since in this part of the analysis we are only interested in differences in shape of control signals to the muscles and not in differences in amplitude, maximal and submaximal SREMG histories were normalized to unit variance. After PCA for each muscle the fractions found were averaged across subjects.

Relative timing of control signals. To detect differences in relative timing of control signals to the muscles, the onset of activity for each muscle was determined for both maximal and submaximal jumping. The onset of activity was taken as the instant of first sustained rise of the SREMG above the baseline. The shift in onset time for each muscle was averaged across subjects and it was tested whether the averaged shift differed significantly from zero using a Student *t*-test for paired comparisons at a level of significance of 5%.

Computer Simulations Using a Model of the Human Musculoskeletal System

Computer simulations of the push-off phase of a vertical squat jump were performed using a model of the human musculoskeletal system which has already been described in detail elsewhere (e.g., 1,11). In short, the model consists of four rigid segments, representing feet, lower legs, upper legs, and upper body, connected in frictionless hinge joints. Six important muscle groups for extension of the lower extremities (m. gastrocnemius, m. soleus, hamstrings, mm. vasti, m. rectus femoris, and m. gluteus maximus) are incorporated into the model by means of Hill-type muscle models. Each muscle model consists of two sets of equations, one describing the contractile behavior of muscle, the other describing its excitation by the central nervous system. The former will be called the contraction dynamics of the muscle model, the latter its excitation dynamics. For the human calf muscles, parameter values for both the excitation and contraction dynamics are available which have been determined on the basis of experimental data obtained from these muscles (14). Numerical techniques used for this purpose have been evaluated first for rat isolated skeletal muscle before being used on data from human muscle (see e.g., 12,13). Because presently data pertaining to both excitation and contraction dynamics are not available for other muscle groups than m. triceps surae, it was decided to use these parameter values for all six muscle groups incorporated in the model. Input to the model is stimulation to each of the six muscles, i.e., a number between 0 and 1 being a one-dimensional representation of recruitment and firing rate of the a motoneurons (5). Among the output of the model is movement of the body segments.

Besides excitation and contraction dynamics, the dynamics of neural control signals can be a functional factor in the control of movement. These dynamics will be referred to as stimulation dynamics. For isometric contractions of the calf muscles, it was shown in (15) that stimulation dynamics was a functional factor influencing the rate of muscle moment development. The effect of stimulation dynamics was incorporated into the model by letting control signals to all muscles rise at a finite rate to their final values. This rate was chosen to be the same for all muscles and corresponded to the rate of change of the averaged SREMG signals during maximal jumping, averaged over all muscles. In the simulations, the stimulation to each muscle was allowed to change only once from its initial value to its maximal value of 1 and was forced to remain maximal during the rest of the simulation. This reduced the control problem of vertical jumping to finding that combination of six muscle stimulation onset times which yielded the highest performance in terms of jump height. The numerical experiments consisted in the first place of finding by means of numerical optimization that combination of onset times of the stimulation to the six muscles which yields the highest jump. Secondly, the stimulation to the muscles in the model was adapted according to the differences in SREMG signals between submaximal and maximal jumps as observed in the experiments. Finally, performance of the model using these new control signals was evaluated.

TABLE 1. Jumping parameters of maximal and submaximal jumps.

Parameter	Maximal Jump	Submaximal Jump
jump height [m]	0.39 ± 0.05	0.31 ± 0.04
$V_{cm}^{toe\text{-}off}$ [m·s^{-1}]	2.4 ± 0.2	2.1 ± 0.3
F_{peak} [*N*]	2100 ± 400	2100 ± 400
$\theta_h^{initial}$	1.4 ± 0.2	1.4 ± 0.2
$\theta_h^{toe\text{-}off}$	2.9 ± 0.1	2.8 ± 0.1
$\theta_k^{initial}$	1.7 ± 0.2	1.7 ± 0.3
$\theta_k^{toe\text{-}off}$	3.0 ± 0.1	2.9 ± 0.2
$\theta_a^{initial}$	1.5 ± 0.1	1.5 ± 0.1
$\theta_a^{toe\text{-}off}$	2.6 ± 0.1	2.4 ± 0.3

$V_{cm}^{toe\text{-}off}$, vertical velocity of the CM that the instant of toe-off; F_{peak}, maximal value attained by the vertical ground reaction force during the push-off phase; $\theta_h^{initial}$, initial hip angle; $\theta_h^{toe\text{-}off}$, hip angle at the instant of toe-off; $\theta_k^{initial}$, initial knee angle; $\theta_k^{toe\text{-}off}$, knee angle at the instant of toe-off; $\theta_a^{initial}$, initial ankle angle; $\theta_a^{toe\text{-}off}$, ankle angle at the instant of toe-off.
For each joint full extension corresponds to π radians. The parameter values shown (mean ± SD) are averages across subjects ($N = 8$).

RESULTS

Experimental Data

In this section, the focus will be on the data of the vertical ground reaction force and SREMG recordings, since the former directly relates to the movement of the CM of the body and thus to performance and the latter is a measure for control signals to the muscles. Table 1 shows jumping parameters of the maximal and submaximal jump averaged across subjects. The difference between maximal and submaximal jump height amounted to 8 cm on average. Figure 2 shows for one subject stick diagrams of the initial position and the position at toe-off. In Figure 2 as well as in the remainder of this paper, solid curves pertain to averaged maximal jumps and dashed curves to averaged submaximal jumps. From Table 1 and Figure 2, it is apparent that subjects were able to reproduce the same initial position fairly well using the device shown in Figure 1. Also, it is interesting to observe that in case of submaximal jumping hip and knee joints are extended less at toe-off. The angular displacement of hip and knee joint (i.e., the difference between joint angle at toe-off and initial joint angle) was found to be significantly less ($P < 0.05$) in submaximal jumping than in maximal jumping. For the ankle joint no significant difference in angular displacement was found between maximal and submaximal jumping. Figure 3 shows for the same subject the vertical ground reaction force for

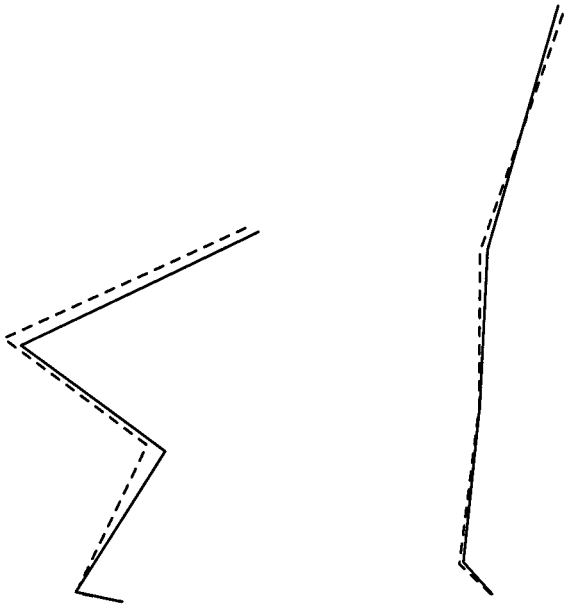

Figure 2—Averaged stick diagrams for one subject. *Left:* starting position, *right:* position at toe-off. *Solid:* averaged maximal jump (N = 3), *dashed:* averaged submaximal jump (N = 3).

both the averaged maximal and submaximal jump. From this figure it can be seen that in case of submaximal jumping, the vertical ground reaction force differs in two aspects to the one of maximal jumping. In the first place, at the start of the movement the vertical component of the ground reaction force rises less steeply in case of submaximal jumping. Secondly, the submaximal jump has a longer push-off phase. Both these features were observed in four of the eight subjects. In two of the other subjects, the vertical component of the ground reaction force also rose less steeply at the onset of the explosive phase, but the movement as a whole was not longer. Of the remaining two subjects, one performed countermovement jumps despite the explicit instruction not to do so. In the last subject the

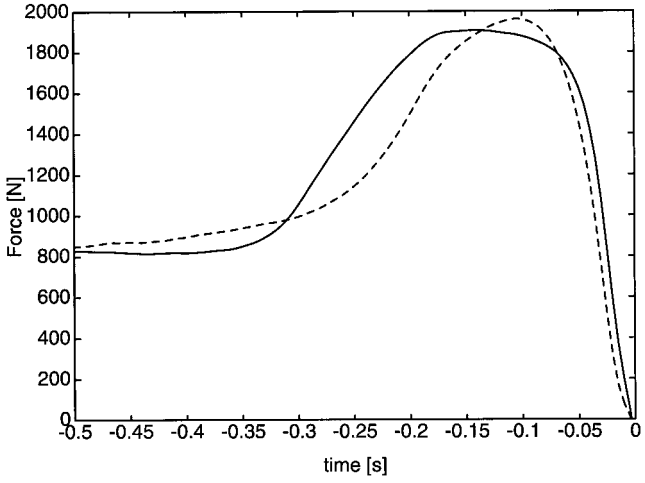

Figure 3—Averaged vertical ground reaction force histories for one subject for both averaged maximal jumps (*solid lines, N* = 3) and averaged submaximal jumps (*dashed lines, N* = 3). Time is expressed relative to toe-off (t = 0).

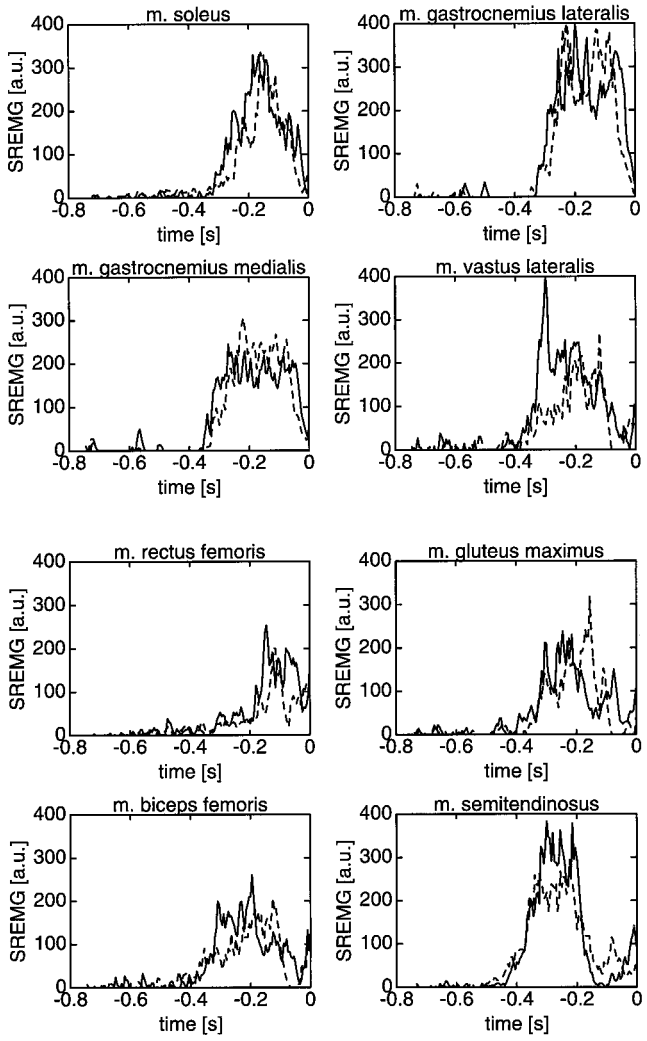

Figure 4—Averaged smoothed rectified electromyographic histories (SREMG histories) of all muscles of one subject. Baseline activity has been subtracted from each curve. *Solid lines* pertain to averaged SREMG histories recorded during maximal jumps (N = 3), *dashed line* to SREMG histories recorded during submaximal jumps (N = 3). Time is expressed relative to toe-off (t = 0).

amplitude of the vertical ground reaction force as a whole was reduced in amplitude, not only the first part in case of submaximal jumping. Finally, the time between the beep signal and the first detectable movement of the CM of the body amounted on average to 550 ms. No significant difference in this time between maximal and submaximal jumps was found.

It is encouraging that kinetic data show similar differences between maximal and submaximal jumps (i.e., less steep rise of the vertical component of the ground reaction force in case of submaximal jumping) for the majority of the subjects. In order to investigate whether a similar control strategy was responsible for these similar kinematic findings in the majority of the subjects, differences in control signals were studied between maximal and submaximal jumping as reflected in the SREMG histories. Figure 4 shows for the same subject as in Fig. 2 averaged SREMG histories for all muscles in both maximal and submaximal jumping. Note

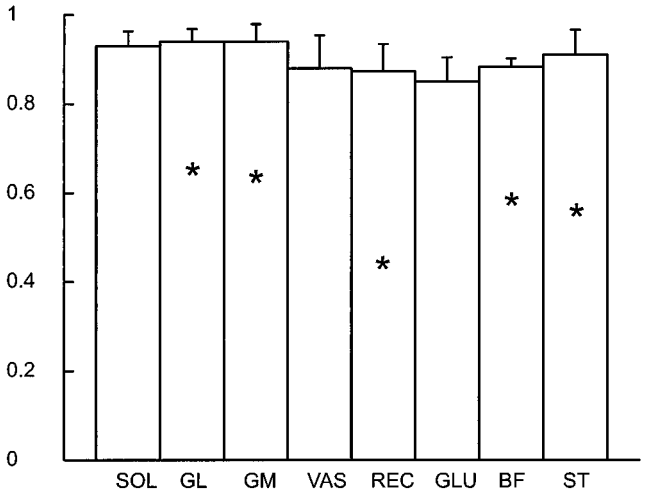

Figure 5—Averaged ratios of time integrals of the SREMG of submaximal and maximal jumps averaged across subjects ($N = 8$). SOL: m. soleus; GL: lateral head of m. gastrocnemius; GM: medial head of m. gastrocnemius; VAS: m. vastus lateralis; REC: m. rectus femoris; GLU: m. gluteus maximus; BF: m. biceps femoris; ST: m. semitendinosus. *Vertical bars* indicate standard deviations. An *asterisk* indicates a ratio which is significantly different from 1.0. ($P < 0.05$).

that SREMG amplitude is reduced in, e.g., m. semitendinosus and m. biceps femoris in case of submaximal jumping. Besides this, onset times of some muscles are shifted in case of submaximal jumping, as can be seen for m. soleus and m. gastrocnemius.

Differences in SREMG amplitude were quantified by computing for each muscle the ratio of the time integrals of the SREMG histories in submaximal and maximal jumping. Figure 5 shows bar graphs of these ratios, averaged across subjects. For all biarticular muscles, the amplitude of the SREMG signals was reduced ($P < 0.05$) in the case of submaximal jumping.

Next, differences in shape of the SREMG histories between maximal and submaximal jumping were quantified by performing PCA on SREMG histories in maximal and submaximal jumping. Figure 6 shows for each muscle the fraction of variance explained by the first principal component. This fraction is about 0.9 for all muscles, with no large differences between muscles. Flanders (3) reported for pointing movements that the first PC often accounted for over 80% of the variance of a set of EMG traces for each muscle. On this basis of these results, a control strategy based on amplitude modulation and temporal shifting of a single basic waveform for each muscle was proposed. Since the fractions of explained variance by the first PC found in this study are somewhat higher than those reported in (3), it seems likely that for each muscle a single waveform is involved in the control of vertical jumping. It is interesting to observe that the shape of the control signals of the muscles which have their amplitude reduced in submaximal jumping, does not change. This is reflected in the fact that for these muscles the fraction of explained variance by the first principal component is not less than that for the muscles in which the amplitude is not reduced in case of submaximal jumping. So it is tempting to conclude that it is primarily the amplitude of the controls to the muscles that is modulated by the CNS in order to perform a submaximal jump.

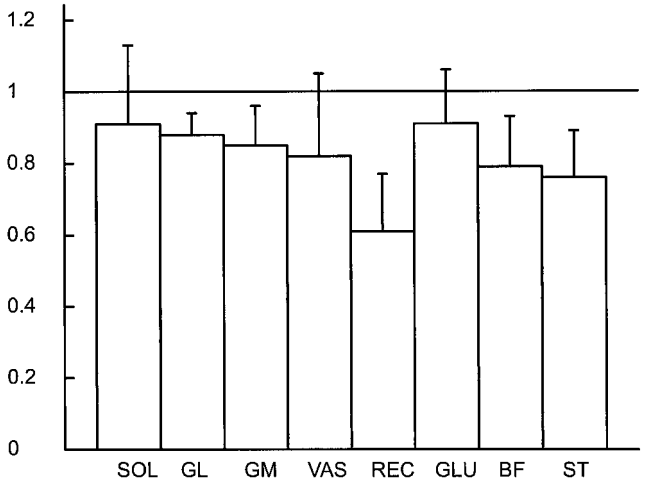

Figure 6—Averaged fractions of explained variance by the first principal component. Data are averaged across subjects ($N = 8$). Abbreviations of muscles are the same as in Figure 5. *Vertical bars* indicate standard deviations.

Finally, SREMG histories were searched for differences in onset times between maximal and submaximal jumping. Figure 7 shows for each muscle the averaged shift in onset times of SREMG signals between maximal and submaximal jumping. Note that time is expressed relative to toe-off, so earlier means further away from toe-off and later means closer to toe-off. From this figure it can be seen that in case of submaximal jumping, the onset times of m. semitendinosus and m. gluteus maximus are shifted to instants earlier in the push-off and the onset time of m. soleus is shifted to an instant later in the push-off. There appears to be a tendency for the more proximal muscles to have their onset times earlier in the movement and for the distal muscles to have their onset times later on in case of submaximal jumping, which is consistent with the fact that the submaximal jump has a longer push-off phase.

The data presented in Figures 2–7 indicate that control signals used by human subjects to perform maximal and submaximal squat jumps are strongly related, since for many muscles no differences in amplitude, shape or relative timing of SREMG histories were found between maximal and submaximal jumping. However, for m. semitendinosus, m. biceps femoris, m. gastrocnemius, and m. rectus femoris a reduction in SREMG amplitude was found in the case of submaximal jumping. Besides this, it was found that in case of submaximal jumping, the onset times of m. gluteus maximus and m. semitendinosus were shifted to instants earlier in the movement, whereas that of m. soleus occurred later in movement. Based on these observations, it may be speculated that a rule is used by the CNS to adjust parameter values in a generalized motor program for vertical jumping that results in an amplitude reduction of control signals to the biarticular muscles, while keeping the amplitude of the control to the other muscles the same. Besides this, the duration of the push-off is increased by shifting onset times of control signals of proximal muscles to earlier in the

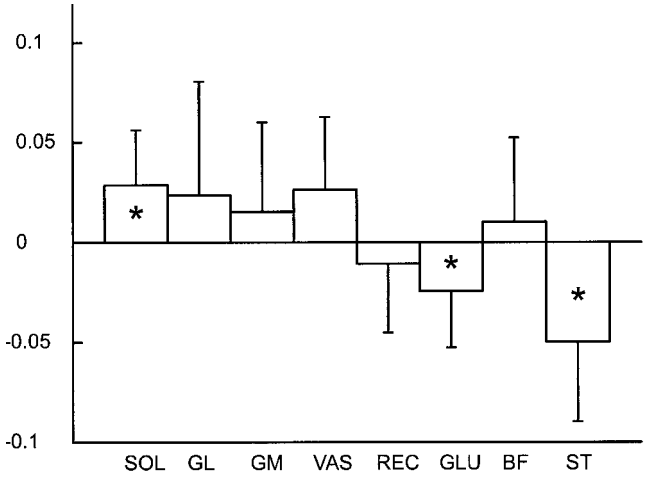

Figure 7—Averaged shift in onset times in seconds for all muscles between submaximal and maximal jumping. A negative shift indicates that a muscles switches on earlier with respect to toe-off in case of submaximal jumping. Data are averages across subjects ($N = 8$). Abbreviations are the same as in Figure 5. *Vertical bars* indicate standard deviations. An *asterisk* indicates a shift in onset time which is significantly different from zero ($P < 0.05$).

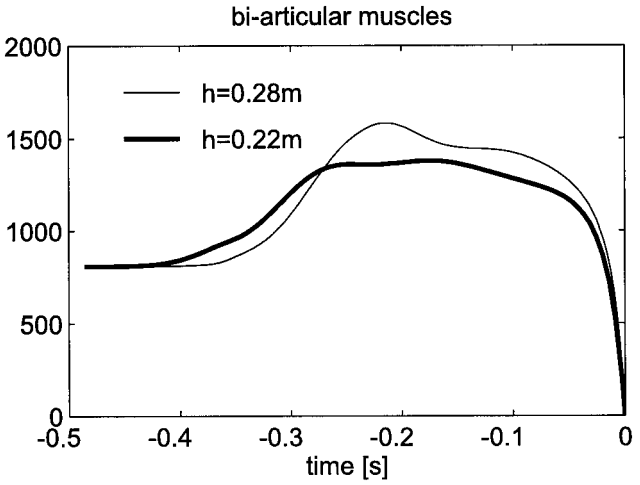

Figure 8—Vertical ground reaction force histories generated in simulation of both maximal and submaximal squat jumps. Time is expressed relative to toe-off ($t = 0$). *Thin line:* simulation of a maximal height squat jump. *Thick line:* submaximal jump obtained manipulation of muscle control signals pertaining to the maximal height squat jump. In this case, maximal amplitude of control signals to all biarticular muscles was reduced to 0.25 and onset times of HAM and GLU have been shifted to an instant 15 ms earlier in the push-off and that of SOL to an instant 15 ms later in the push-off.

push-off and those of distal muscles to later on in the push-off.

Computer Simulations

To investigate whether the changes in control signals pertaining to a maximal jump as derived in the previous section from analysis of SREMG histories are sufficient to obtain submaximal performance, computer simulations of the push-off phase in vertical squat jumping were performed. To this end, control signals for a maximal height squat jump were obtained by numerical optimization of onset times of the six muscles in the model. Subsequently, these control signals were systematically manipulated by changing control signals to the muscle for which in analysis of SREMG significant differences in either SREMG amplitude or SREMG timing were found between maximal and submaximal jumping. This meant in the first place, that maximal stimulation to hamstrings, m. gastrocnemius, and m. rectus femoris was reduced. Secondly, onset times of m. gluteus maximus and hamstrings were shifted to instants earlier in the push-off and that of m. soleus to instants later in the push-off. Unfortunately, when amplitude of control signals to the biarticular muscles was reduced according to the ratios of time integrals of SREMG signals, as obtained in the experiments, the corresponding reduction in jump height was only 2 cm, which is much smaller than observed in the experiment. This is due to the fact that in the model used for excitation dynamics (5), the equilibrium level of active state (the scaling factor for maximal force) is already 95% of its maximum at stimulation levels of the order of 0.4. Therefore, it was investigated whether larger reductions in amplitude of control signals led to submaximal jumps of comparable height as those observed in human subjects. Figure 8 gives an example of such a simulation in which the maximal amplitude of control signals to all biarticular muscles is reduced to 0.25, with maximal amplitude of control signals to all monoarticular muscle remaining unity. Besides this, the onset times of both m. gluteus maximus and hamstrings have been shifted to an instant 15 ms earlier in time and that of m. soleus 15 ms later in time. In this case, jump height is reduced by 6 cm, which is comparable to the differences between maximal and submaximal squat jumps in the experimental part of the paper. Interestingly enough, the two key features observed in the experimental data are more or less reproduced in the model calculations. In the first place, peak amplitude of the vertical ground reaction force remains about the same between maximal- and submaximal jumping. Secondly, the duration of the push-off increased in case of submaximal jumping in the model. Both the amplitude reduction of control signals to the biarticular muscles and the shift in onset times contributed to this increased duration of the push-off in case of submaximal jumping. Although such simulation results give some confidence that the rule inferred from analysis of experimental SREMG signals could be sufficient to obtain behavior as observed experimentally, it is clear that still marked differences remain between model calculations and experimental data.

DISCUSSION

In this paper, we set out to determine in the first place whether different subjects performed submaximal squat jumps of predefined height in a similar way. Although, unfortunately, no evidence for scaling of joint movements and hence identical kinematics at different speeds was found, it was shown that the vertical component of the ground reaction force displayed similar characteristics in the

majority of subjects, the most important being a less steep rise at the onset of the explosive phase in case of submaximal jumping. Secondly, it was investigated to what extent control signals generated by the CNS in case of submaximal jumping are related to control signals generated in case of maximal height jumping. For this purpose, SREMG histories recorded during maximal and submaximal squat jumping were analyzed on differences in amplitude, shape, and relative timing. This analysis revealed for all biarticular muscles a reduction in SREMG amplitude in case of submaximal jumping and a shift in onset times for some proximal muscles to instants earlier in the push-off and for some distal muscles to instants later in the push-off in case of submaximal jumping. Control signals used to perform submaximal squat jumping were strongly related to those used to perform maximal height squat jumps. Besides this, it was shown using a model of the human musculoskeletal system that when control signals pertaining to a maximal jump were adapted according to the differences in control between maximal and submaximal jumping, as derived from the SREMG recordings, the model performed a submaximal jump that displayed similar characteristics as submaximal jumps performed by human subjects.

The strong relationship found between SREMG signals recorded during maximal and submaximal squat jumping seems to support the hypothesis that within the CNS there exist template motor programs for classes of movements, the output of which is determined by the setting of certain parameters. Within this framework, a simple rule for adjustment of parameter values within this template motor program would be sufficient to make the CNS provide appropriate control signals in case of both maximal and submaximal squat jumping. Such a rule would simplify the control problem for vertical squat jump considerably, since it drastically reduces the number of control signals which need to be stored within the CNS. On the basis of the present experimental data, the exact nature of the rule presumably used by the CNS to obtain control signals for vertical squat jumping remains unclear. Only its results, the fact that muscle control signals in case of submaximal vertical squat jumping can be related to those of maximal vertical squat jumping by means of amplitude reduction and temporal shifting, are known. Within this context, construction of a mathematical model of the CNS can help to provide more insight into what neural mechanisms are necessary to obtain similar transformations of muscle control signals as observed in this study.

A second issue that deserves attention is why it is just the activity of the biarticular muscles that is modulated in order to obtain submaximal performance in vertical jumping. Often, a special role is attributed to biarticular muscles in the coordination of multijoint movements since they link the movements in different joints together (see e.g., 7). So one may speculate that this special role makes these muscles particularly suited to be modulated in activity in order to obtain submaximal performance.

Finally, results coming from the forward dynamic computer simulation need further discussion. From the results presented in Figure 8, it is apparent that the model is indeed capable of producing submaximal jumps which resembled submaximal jumps of human subjects to some extent when control signals to the muscles were adapted according to differences observed in SREMG signals in maximal and submaximal jumping. However, differences remain between the simulated and experimental results. These differences may be readily due to our imperfect knowledge of properties of the real human musculoskeletal system. For the human calf muscles, much effort was taken to determine parameters in both the excitation and contraction dynamics as accurately as possible on the basis of experimental data (see also: 13–15). For other muscle groups, such data are currently not available. Especially, it is unknown whether excitation and contraction dynamics vary strongly from one muscle group to another. Owing to this lack of experimental data, it does not come as a big surprise that there remain a number of differences between experimental data and model calculations. Qualitatively, however, the correspondence between the two is encouraging. Without doubt, also the quantative correspondence between the two will improve as soon as more experimental data on human muscle will become available.

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